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Lateral shearing interferometry for high-NA EUV wavefront metrology

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ABSTRACT

We present a lateral shearing interferometer suitable for high-NA EUV wavefront metrology. In this interferometer, a geometric model is used to accurately characterize and predict systematic errors that come from performing interferometry at high NA. This interferometer is compatible with various optical geometries, including systems where the image plane is tilted with respect to the optical axis, as in the Berkeley MET5. Simulation results show that the systematic errors in tilted geometries can be reduced by aligning the shearing interferometer grating and detector parallel to the image plane. Subsequent residual errors can be removed by linear fitting.

Keywords: Lateral shearing interferometry, Wavefront sensing, EUV extendibility, Aberrations

1. INTRODUCTION

As the semiconductor industry advances, the resolution of EUV optical systems becomes higher and higher. Next- generation EUV exposure tools will have numerical apertures (NA) exceeding 0.5, providing an ultimate resolution below 8 nm. However, in order to reach this resolution, the optical aberrations must be characterized and removed.

Presently, the most commonly used method for measuring EUV litho tools is lateral shearing interferometry (LSI). LSI eliminates the need for a high quality reference wave by interfering the test wavefront with shifted copies of itself. While LSI has shown great success measuring EUV systems with small to medium NAs (0.01 - 0.35), it has not yet been successfully deployed at higher NA tools (NA > 0.35) [1]. Part of the reason is due to the fact that systematic aberrations resulting from the high incident angles onto the diffraction grating in the interferometer scale as powers of the NA, and can quickly compromise the accuracy of the measurement at high NA.

In this paper, we present a modified LSI to measure EUV wavefronts at high NA. The key to this method is building a model that accurately simulates the systematic errors resulting from the given geometry of the tool, which are subtracted during the reconstruction. Because of this, this method can theoretically extend to not only high NA, but also to non-telecentric geometries. This represents an important improvement in the method, since previous versions of LSI required the interferometer to be perpendicular to the optical axis, which is not compatible with tools like the Berkeley MET5.

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2. THEORY

2.1 LSI geometry

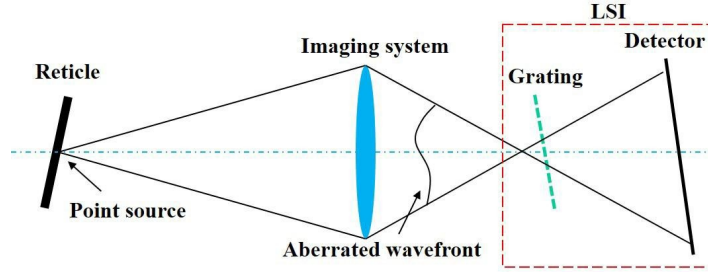


Fig. 1 Schematic of LSI on the Berkeley MET5

A schematic of the LSI as implemented in the Berkeley MET5 is shown in Fig. 1. A pinhole array patterned onto the reticle serves as a spatial filter that fills the test optic pupil. After passing through the imaging system, the wave picks up aberrations from the optics. This aberrated wavefront is then incident on a 2-dimensional grating, and the diffracted orders interfere on a CCD. The grating and detector are tilted 1.12 degrees with respect to the optical axis, which is necessary for satisfying the tilt conjugate criterion in the Berkeley MET5 (these angles are exaggerated in the schematic for clarity).

2.2 2-ray model

To understand the systematic errors that result from this geometry, a simple ray-optics model called the “2-ray model” is developed. In this model, zeroth and first order diffracted wavefronts are considered to be rays that interfere at the detector, and the phase difference due to differing optical pathlengths is computed geometrically. In this section we present a mathematical description of the 2-ray model in one dimension, although the extension to two dimensions is straightforward.

A diagram of the relevant parameters is shown below in Fig. 2.

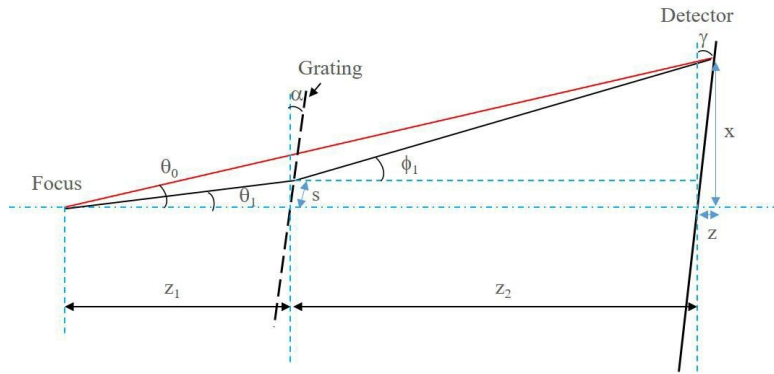


Fig. 2 2-ray model

The phase difference between the two rays can be expressed as

$$\Delta \varphi(x) = \frac{2\pi}{\lambda} L_1 + \frac{2\pi s}{\lambda} - \frac{2\pi}{\lambda} L_0, \quad (1)$$

where λ is wavelength, L_0 and L_1 are the respective path lengths of the rays, which can be expressed as

$$L_0 = (z_1 + z_2 + z) \sec \theta_0$$

$$L_1 = \left(\frac{z + s \sin \alpha}{\cos \phi} \right) \sec \theta_1 + \left(\frac{z - s \sin \alpha}{\cos \phi} \right) \sec \theta_2, \quad (2)$$

where z_1 and z_2 are the distances from grating to focus and detector, respectively; $z = x \tan \gamma$; α is the grating tilt angle; and 2π accounts for the phase acquired by the 1st order ray as it diffracts off of the grating, where T is grating pitch and s is the off length, which can be expressed as

$$s = \frac{z_1 \sin \theta_1}{\cos(\theta_1 + \alpha)} \quad (3)$$

θ_0 is the angular position of the coordinate x measured from the test wave focus and is given by

$$\theta = \tan^{-1} \left(\frac{x}{z_1 + z_2} \right) \quad (4)$$

In Eq. (2), θ_1 and ϕ_1 are unknown, but can be determined by noting that:

1. The lateral position of the two rays must coincide at the detector:

$$(z_1 + z_2) \tan \theta_0 = (z_1 + s \sin \alpha) \tan \theta_1 + (z_2 - s \sin \alpha) \tan \phi_1 \quad (5)$$

2. θ_1 and ϕ_1 must satisfy the grating equation:

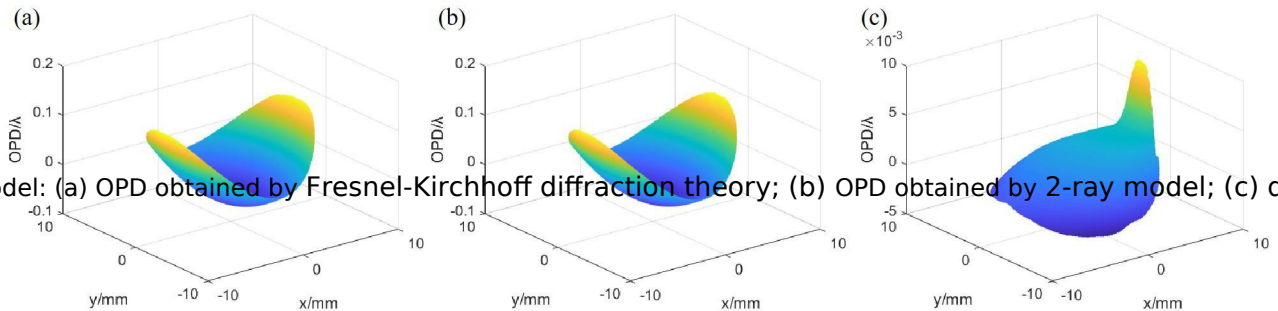
$$\sin(\theta_1 + \alpha) = \sin(\phi_1 + \alpha) - \frac{\lambda}{T} \quad (6)$$

The system of equations consisting of Eqs. (5) and (6) can be solved numerically.

2.3 Model validation

In order to verify the validity of the 2-ray model, we compare it with a Fresnel-Kirchhoff diffraction model. This diffraction model represents a rigorous numerical solution to interferogram, but is computationally expensive; one interferogram solution takes over 30 minutes to compute on a standard PC, whereas the 2-ray model computes in less than a second. Fig. 3(a) shows the OPD extracted from the shearing interferogram from the interference of the 0 and +1 orders. A corresponding result solved by the 2-ray model is shown in Fig. 3(b). Fig. 3(c) presents the difference between the two results showing a good agreement, with an RMS error of 0.0016λ .

The fact that the 2-ray model accurately predicts the interferograms in LSI with an arbitrary NA, grating tilt and detector tilt is a major breakthrough in the method.



The 2-ray model provides a quick way to model the effects of LSI geometry on the systematic aberrations in the reconstruction. The simplest way to understand these aberrations is by considering the “null interferogram”, or the interferogram formed by an ideal spherical wavefront. If there were no systematic errors in the LSI method, then reconstructing the null interferogram should reproduce a perfect spherical wavefront. Any residual aberrations in the

reconstructed wavefront represent systematic aberrations, imparted by the method itself rather than the wavefront; these aberrations must be subtracted out in order to get an accurate result.

Fig. 4 shows the computed null interferogram using $NA=0.5$, $T=234\text{nm}$, $\lambda =13.5\text{nm}$, $z_1 =1\mu\text{m}$, and a grating tilt 1.12 degrees, which is parallel to the wafer conjugate plane in the Berkeley MET5. The resulting wavefront has an RMS error of 0.5 nm.

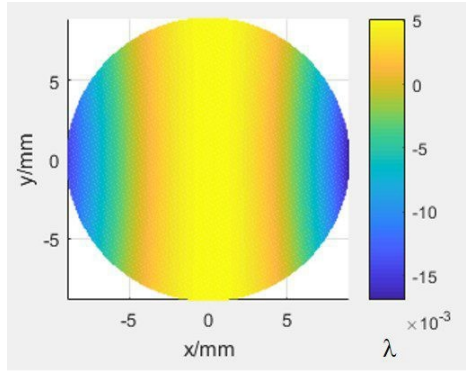
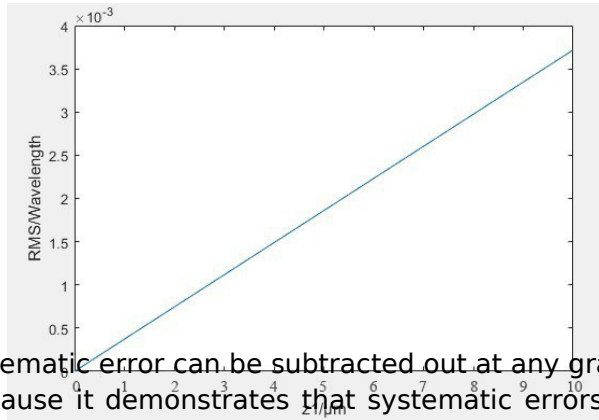


Fig. 4 Phase contained in null interferogram with the grating tilt 1.12 degree

From this model, we found that the magnitude of this error is proportional to the distance between the grating and the optic focus, z_1 . Using the 2-ray model we computed several different geometries with varying grating distance. The results are summarized in Fig. 5, which demonstrates this linear relationship:



While theoretically the systematic error can be subtracted out at any grating distance, this linear relationship is valuable because it demonstrates that systematic errors go away at $z_1 = 0$.

Although it may not be experimentally practical to operate exactly in the focus of the optic, we can take measurements at various values of z_1 , and use the errors to fit a line

and extrapolate the value at focus.

Fig. 5 RMS values of the systematic errors vs. z_1

3. EXPERIMENTAL RESULTS

To demonstrate this modified LSI, it was deployed in the commissioning of the 0.5-NA Berkeley MET5. Here the grating pitch is chosen to be 234 nm which gives a shear ratio of 5%, and the grating distance z_1 is set at 600 nm. Grating tilt is controlled using a 6-axis hexapod on which the grating is mounted. The grating tilt was set to be 1.12

degrees, which is the nominal conjugate plane of the wafer. The grating consists of an 80-nm nickel absorber patterned onto a 100-nm silicon membrane. The interferogram is captured onto an in-vacuum CCD mounted on a 2-axis goniometer for controlling the detector tilt angle. The detector is positioned to be parallel to the grating, also at 1.12 degrees.

Fig. 6(a) and (b) shows the interferograms in x and y directions, and Fig. 6(c) and (d) show the phase of the x- and y- derivatives of the wavefront which is extracted using a phase-shifting approach. Fig. 6(e) shows the reconstructed wavefront after the systematic errors are subtracted. The resulting RMS wavefront value is 0.063λ , or 0.85 nm.

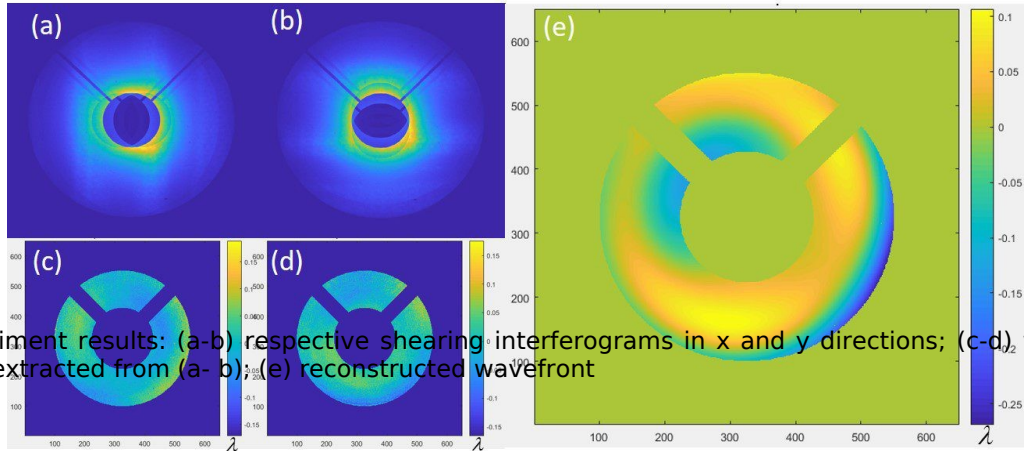


Fig. 6 Experiment results: (a-b) respective shearing interferograms in x and y directions; (c-d) wavefront derivatives extracted from (a- b); (e) reconstructed wavefront

4. DISCUSSION

The versatility of this modified LSI reconstruction comes from its ability to model a wide range of optical geometries. The standard version of LSI only works at low NA and with its grating aligned to the optical axis because it relies on systematic aberrations being negligible. The modified LSI model leverages its ability to quickly and accurately compute the systematic errors for an arbitrary imaging geometry, which means that even if these errors are non-zero, they can be removed. This may play an important role for next generation EUV litho tools which may have even higher NA or more exotic optical geometries.

One important aspect of any method like this one that assumes knowledge of systematic errors, is accurately modeling the optical geometry. If the assumptions about this geometry are incorrect, then the systematic errors will be not computed correctly and the resulting reconstruction will be compromised. For this reason, when measuring the Berkeley MET5, we chose to minimize the grating distance to focus, which is proportional to the systematic errors in this geometry. This way if there were small errors in the measurement of this distance, or other parameters such as the grating or detector tilt, then the additional error would not make a significant difference in the reconstructed wavefront.

When used correctly, we believe this is a powerful method for characterizing aberrations on high-NA EUV systems and can play an important role in the development and alignment of next-generation EUV litho tools.

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